HYBRIDIZING CONCENTRATED SOLAR POWER (CSP) WITH BIOGAS AND BIOMETHANE AS AN ALTERNATIVE TO NATURAL GAS: ANALYSIS OF ENVIRONMENTAL PERFORMANCE USING LCA.

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ABSTRACT: Concentrating Solar Power (CSP) plants typically incorporate one or various auxiliary boilers operating in parallel to the solar field to facilitate start up operations, provide system stability, avoid freezing of heat transfer fluid (HTF) and increase generation capacity. The environmental performance of these plants is highly influenced by the energy input and the type of auxiliary fuel, which in most cases is natural gas (NG). Replacing the NG with biogas or biomethane (BM) in commercial CSP installations is being considered as a means to produce electricity that is fully renewable and free from fossil inputs. Despite their renewable nature, the use of these biofuels also generates environmental impacts that need to be adequately identified and quantified. This paper investigates the environmental performance of a commercial wet-cooled parabolic trough 50 MWe CSP plant in Spain operating according to two strategies: solar-only, with minimum technically viable energy non-solar contribution; and hybrid operation, where 12 % of the electricity derives from auxiliary fuels (as permitted by Spanish legislation). The analysis was based on standard Life Cycle Assessment (LCA) methodology (ISO 14040-14040). The technical viability and the environmental profile of operating the CSP plant with different auxiliary fuels was evaluated, including: NG; biogas from an adjacent plant; and BM withdrawn from the gas network. The effect of using different substrates (biowaste, sewage sludge, grass and a mix of biowaste with animal manure) for the production of the biofuels was also investigated. The results showed that NG is responsible for most of the environmental damage associated with the operation of the plant in hybrid mode. Replacing NG with biogas resulted in a significant improvement of the environmental performance of the installation, primarily due to reduced impact in the following categories: natural land transformation, depletion of fossil resources, and climate change. However, despite the renewable nature of the biofuels, other environmental categories like human toxicity, eutrophication, acidification and marine ecotoxicity scored higher when using biogas and BM.

Keywords: Concentrated Solar Power (CSP), Life Cycle Assessment (LCA), biogas, natural gas, biomethane.

1 INTRODUCTION

With over 100 commercial projects in operation or under construction worldwide and an installed capacity expected to reach 10.0 GWe in 2015, Concentrated Solar Power (CSP) has the potential to play a major role in the decarbonisation of the existing energy model [1-2]. Depending on the characteristics of the solar collectors, CSP plants may adopt different configurations. Parabolic trough collectors are the most mature and widely deployed of the CSP technologies, representing over 85 % of the installed capacity worldwide. These plants use parabolic mirrors with sun tracking systems to concentrate direct solar irradiation into a tube receiver that runs along the focal point of the collector. A Heat Transfer Fluid (HTF) circulating inside the receiver absorbs the solar energy to increase its temperature from around 295 ºC in the cold end of the system to 395 ºC at the exit of the solar field. The hot HTF is subsequently circulated through a series of heat exchangers for the generation of superheated steam (typically at 100 bars/375 ºC). This steam is employed to drive a turbine for electricity generation, as in conventional Rankine cycles. Modern CSP plants usually incorporate thermal energy storage (TES) systems based on molten nitrate salt mixtures to increase the number of operating hours and their capacity factor [3].

Commercial CSP plants also include one or more auxiliary boilers that provide extra heat for daily start-up operations, to avoid freezing of the HTF and molten salts, to reduce system instability caused by transient clouds and also for additional electricity generation. Natural Gas (NG) is used most frequently as auxiliary fuel due to its low cost, clean combustion and rapid response, although the use of fuel oil, mineral coal and biomass has also been reported [3-6]. The minimum amount of auxiliary energy required to operate a commercial CSP installation varies depending on plant size and design, the characteristics of the TES system, the intensity and daily hours of solar irradiance, and also ambient temperature. For a CSP plant like the one investigated in this paper (wet-cooled, 50 MWe, parabolic trough, 7.5 hours TES), this minimum requirement has been estimated to be between 100,000-130,000 MJ/MW/yr. It may be assumed that this energy input does not have a net contribution to electricity generation.

The Spanish legislation regulating the generation of electricity from sustainable resources allows CSP plants to produce up to 12 % of their electricity from auxiliary fuels [7]. For a typical 50 MWe installation, this hybrid operation involves the consumption of $2.32 \cdot 10^8$ MJ/yr of auxiliary fuel and results in the generation of 22,600 MWh/yr of additional electricity, which also benefits from the 26.9 c€/kWh premium fee established for solar thermal power generation. Hence, all commercial CSP plants in Spain (39 in operation and 21 currently under construction) operate according to this strategy in order to maximize economic revenues. Note that this legislation was superseded by Royal Decree Law 1/2012, which removed financial support for future installations not approved under the previous regime. A few authors have investigated the environmental performance of CSP plants based on parabolic through technology using Life Cycle Analysis (LCA) methodology [8-12]. These investigations suggest that the environmental performance of these plants is highly influenced by the energy input and the type of fuel (mainly NG) employed in auxiliary boilers [9]. An alternative discussed in specialized forums involves replacing the NG with biomass derived fuels, so that the resulting electricity could be regarded as being fully renewable and totally independent from fossil resources.

Spain produced in 2010 the equivalent of $5.19 \cdot 10^8$ MJ of raw biogas, of which 60.2 % was obtained in landfill sites, 6.2 % was produced by digestion of sewage sludge in wastewater treatment plants and the remaining 33.5 % was produced from other substrates (mainly agricultural and farm waste). This generation capacity is still far from that of Germany, the largest producer of biogas in Europe, who produced $2.80 \cdot 10^{10}$ MJ equivalent of raw biogas in 2010 [10]. The Spanish Plan for Renewable Energies (2010-2020) [11] describes that biogas production in Spain will nearly triple in the period between 2010 and 2020 mainly as a result of the coming into operation of centralized plants using farm waste, agro-industrial waste and energy crops as substrates. The possibility of upgrading biogas to biomethane (BM) for injection into the gas grids will open new opportunities for this renewable fuel.

Despite its renewable nature, the production, upgrading, transportation and utilization of biogas also involves environmental costs that need to be adequately identified and quantified. LCA has been reported to be a suitable methodology to evaluate environmental performance of energy systems [13-16].

The aims of this work are threefold: firstly, to evaluate the technical viability and environmental performance of a commercial 50 MWe CSP plant using Life Cycle Analysis (LCA) methodology; secondly, to analyze the effect of operating the installation under solar-only and hybrid conditions (12 % electricity from NG); and finally, to evaluate the technical viability and the environmental consequences associated with replacing this NG with biogas and BM obtained from different substrates.

2 METHODS, OBJECTIVES AND SCOPE

The LCA was conducted according to standardized ISO 14040-4 methodology. The functional unit was the generation of 1 MWh of electricity. The objectives were as follows:

- To quantify the environmental performance of a wet-cooled commercial 50 MWe CSP with 7.5 h TES,
- To analyze the environmental consequences of operating the installation in *solar-only* and also in *hybrid* mode with 12 % energy input from auxiliary fuels, and

- To evaluate the technical viability and the environmental consequences associated with replacing this NG with biogas and BM obtained from different substrates (biowaste, sewage sludge, grass and a mix of biowaste with animal manure).

Unless otherwise indicated, the technical information used in this paper regarding the design, construction and the operating conditions and strategy of the CSP installation was supplied by a team of engineers specialized in CSP plants. ReCiPe Midpoint Europe (H perspective) and ReCiPe Endpoint Europe H/H methods were used for aggregation of environmental impacts, while SimaPro v. 7.3 software was used for calculations.

2.1. Description of the CSP plant

The system under investigation is a wet-cooled 50 MWe CSP plant based on parabolic trough technology located in the Ciudad Real region (Castilla La Mancha, Spain). The plant uses synthetic oil as HTF and incorporates a 7.5 hour molten salt thermal storage system (two tank configuration). Table 1 shows the main specifications of the installation when operating in *solar-only* or in *hybrid* modes. The former implies that all the electricity generated derives from solar irradiation (100 % solar fraction); the latter involves the production of 12 % additional electricity from the combustion of auxiliary fuels, as permitted by Spanish law. It is assumed that the only difference with respect to the configuration of the CSP plant operating in solar-only or hybrid models involves the addition of two 20 MWth auxiliary gas boilers in the latter. Both configurations have a smaller 10 MWth boiler used to avoid freezing of the HTF during the night, the two larger ones incorporated to hybrid mode are intended to increase power capacity by extending operating hours.

Table 1: Specifications of the reference CSP plant operating in *solar-only* and *hybrid* conditions**.**

		Solar-only	Hybrid[a]
Installed capacity (MW)		50	50
Gross electricity output (MWh/yr)		165,687	188,281
Thermal efficiency of the cycle		35%	35%
Net efficiency		16%	16%
Auxiliary boiler efficiency		95%	95%
Lifetime (years)		25	25
Number of solar collectors		624	624
Aperture (m^2)		510,120	510,120
Area occupied (ha)		200	200
Full load hours equivalent (h/yr)		2,800	3,100
Normal Direct Irradiance ($kWh/m^2 \cdot yr$)		2,030	2,030
Storage capacity (hours)		7.5	7.5
Non-solar energy input (MJ/yr)	Maintenance	$6.28 \cdot 10^6$	$6.28 \cdot 10^6$
	Operation	0	$2.32 \cdot 10^8$
Electricity consumption O&M (MWh/yr)	self-consumption	25,962	29,577
	from the grid	550	550

[a] 12 % of electricity output from auxiliary non-solar resources, as permitted by Spanish Royal Decree 661/2007.

The gross electricity output of the CSP plant operating in *solar-only* mode was estimated to be 165,687 MWh/yr, resulting from 2,800 h/yr equivalent of full load operation. Although all the electricity produced by the plant is attributable to solar radiation, the installation still consumes $6.28 \cdot 10^6$ MJ/yr of auxiliary fuel for start-up and maintenance. Operation in *hybrid mode* involves the consumption of the same amount of auxiliary fuel for start-up and maintenance plus an additional $2.32 \cdot 10^8$ MJ/yr for power generation (35 % thermal efficiency of the cycle). This results in an increase in the full load operation capacity of the plant to 3,100 h/yr equivalent, for a yearly electricity output of 188,281 MWh/yr. This additional 22,594 MWh represent the 12 % electricity output allowed by Spanish legislation. It is assumed that 16 % of the electricity generated by the CSP plant is used onsite for operation and maintenance, while the remaining 84 % is poured into the grid for economic revenue. In addition, the installation consumes 550 MWh/yr of electricity from the grid during non-productive hours (mainly due to HTF circulation during the night).

Figure 1 shows the life cycle diagram of the CSP plant under investigation. The following life cycle phases were considered in the analysis: extraction of raw materials; manufacturing of components, transportation of components to the site, construction of the power plant, operation and maintenance, and decommissioning and disposal of components at the end of their useful lives (25 years). The following systems were considered in the inventory data:

- HTF system: synthetic oil, piping, nitrogen production system.
- Solar field: sun collectors (including frame, mirrors and foundations), sun tracking system, controls, vehicle for cleaning collectors.
- Thermal storage: piping, tanks, foundations, insulation, heat exchangers, salts.
- Power block: heat exchanger, steam turbine, generator, deaerator, condenser, piping.
- Facilities: buildings, roads, water treatment plant.

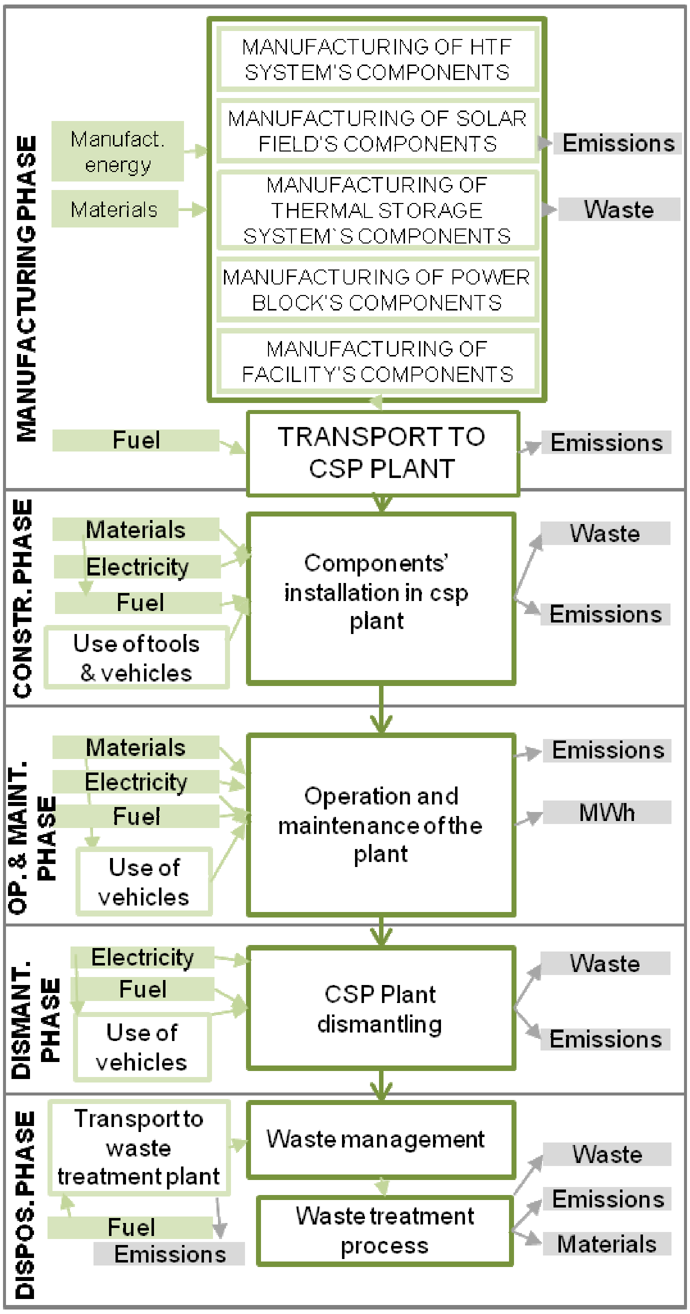

Figure 1: Life cycle flow chart of electricity generation in the CSP plant

No inventory data was available for the following elements: circulation pumps used in the HTF circuit and thermal storage system; foundations required by auxiliary boilers and thermal storage system. The following information was obtained from the scientific literature: inventory data for a generic office building [17]; sun tracking system, inventory data for electricity consumption during demolition; fuel consumption during dismantling activities [11]. The waste management scenario considered in this simulation (40 % recycling; 30 % landfill; 30 % materials recovery) is based on the information published in the Spanish National Plan for Management of Construction and Demolition Waste [18]. EcoInvent v. 2.0 was used to estimate the environmental impact associated with the consumption of raw materials and fuels employed in the construction and operation of the CSP plant, manufacturing and construction of the power block and deionization of refrigerating water used in the power block.

2.2. Analysis of NG and biogas utilization in the CSP plant

Table 2 shows the auxiliary energy inputs required in each of the operating scenarios investigated: solar-only and hybrid mode. The consumption of auxiliary fuels was calculated considering their net calorific values as follows: NG 39.0 MJ/Nm^3; biowaste biogas 24.0 MJ/Nm^3; grass biogas 19.7 MJ/Nm^3; sludge biogas 16.5 MJ/Nm^3; mixed manure biogas 24.0 MJ//Nm^3; and BM 34.5 MJ/Nm^3.

Table 2: Energy and fuel requirements of the CSP plant operating in solar-only and hybrid modes.

SCENARIOS	Auxiliary Energy Input[a] (MJ/yr)	NG	BIOGAS from different substrates				BM
			Biowaste	Mixed manure	Grass	Sewage Sludge	Methane 96%
		Vol. (Nm^3/yr)	Vol. (Nm^3/yr)	Vol. (Nm^3/yr)	Vol. (Nm^3/yr)	Vol. (Nm^3/yr)	Vol. (Nm^3/yr)
Solar-only	$6.28\cdot10^6$	$1.61\cdot10^5$	$2.61\cdot10^5$	$2.61\cdot10^5$	$3.18\cdot10^5$	$2.78\cdot10^5$	$1.82\cdot10^5$
Hybrid	$2.39\cdot10^8$	$6.12\cdot10^6$	$9.93\cdot10^6$	$9.93\cdot10^6$	$1.21\cdot10^7$	$1.06\cdot10^7$	$6.93\cdot10^6$

[a] including maintenance and operation activities

The environmental impact associated with the use of NG was determined by adjusting the data from Ecoinvent v.2.0 to the Spanish import mix in 2012 [19] as follows: Algeria 69 %, Nigeria 16 %, Norway 10.9 % and Netherlands 3.9 %. This data includes the environmental impact associated with the extraction, upgrading and transportation of the NG to the CSP plant. The environmental impact associated with the use of raw biogas from specific substrates was obtained from Ecoinvent v.2.0. The impacts of biogas obtained from *biowaste* (household, yard and food waste) and from *cultivated grass* were estimated considering centralized plants with capacities around 1,000,000 Nm^3/yr. The impact of *mixed manure* biogas was estimated in a 300,000 Nm^3/yr installation utilizing a mixture of liquid manure with fat, oil, cereals, catering waste, vegetables and organic waste. The impact of *sewage sludge* biogas was determined in a 912,500 Nm^3/yr installation associated to a 100,000 per capita equivalent (PCE) wastewater treatment plant. Further information about these biogas plants can be found in chapter 12 of Life Cycle Inventories of Bioenergy from EcoInvent [20]. The environmental impact associated with the use of BM was estimated by addition of the impacts attributed to the production of the raw biogas (as described above), upgrading of the raw biogas into BM using Pressure Swing Adsorption (PSA) technology and transportation via existing gas grids to the CSP plant. The impact associated with biogas upgrading and BM transportation was obtained from EcoInvent [20].

Farm scale biogas facilities typically produce of the order of 10,000-100,000 Nm^3/yr, which would not even be sufficient to feed the CSP plant operating in solar-only mode. Centralized facilities have biogas generation capacities typically in the range between 1 and $5\cdot10^6$ Nm^3/yr, although even larger plants (up to $25\cdot10^6$ Nm^3/yr) operate in specific locations of northern Europe [21]. This suggests that a CSP plant like the one investigated in this paper (50 MWe) operating in hybrid mode (12 % electricity output from auxiliary fuels) could meet its auxiliary energy demand by association with a single very large centralized biogas plants. However, it is unlikely that the same geographical location will meet the requirements for both large scale biogas generation and solar irradiance. An alternative for hybrid mode operation assumed in this work involves using BM as auxiliary fuel. This option involves generation of raw biogas in disperse plants, followed by upgrading into BM, injection and transportation through the gas network for use in the CSP installation.

2.3. Operating scenarios

2.3.1. Solar only mode

As shown in Table 2, solar-only operation of the CSP plant requires the consumption of $1.61 \cdot 10^5$ Nm^3/yr of NG or between $2.61 \cdot 10^5$ and $3.18 \cdot 10^5$ Nm^3/yr of biogas, depending on substrate. Considering the production capacity of biogas installations, it has been assumed that the CSP plant obtains all its auxiliary energy requirements from a centralized biogas plant located in its vicinity. It has been assumed that the raw biogas is transported by pipes without additional processing. The cultivation of grass for biogas generation is not suitable in southern Spain, where the CSP plant under investigation is located. Furthermore, the use of sewage sludge biogas would require the location of the CSP plant near a large wastewater treatment plant, an unlikely location considering the space constraints of the solar power plant. Hence, these two options were not considered in this analysis. The use of BM was not considered in this scenario either due to the reduced consumption and the additional economic and environmental costs associated with upgrading the raw biogas.

2.3.1. Hybrid mode

As shown in Table 2, operation of the CSP plant in hybrid mode would require the provision of $2.39 \cdot 10^8$ MJ/yr from auxiliary fuels, which represents $6.12 \cdot 10^6$ Nm^3/yr of NG, $6.93 \cdot 10^6$ Nm^3/yr of BM or between $9.9 \cdot 10^6$ and $12.1 \cdot 10^6$ Nm^3/yr of biogas, depending on substrate. As discussed above, this volume of raw biogas may only be produced in very large centralized facilities whose geographical location is unlikely to coincide with strong solar irradiance, as required by the CSP plant. Hence, operation of the CSP plant in hybrid mode has been investigated assuming that it uses BM produced from four alternative substrates: grass, biowaste, sewage sludge and mixed manure. In this case, the impact associated with upgrading the biogas to BM, its injection and transportation through the gas grid have also been incorporated into the model.

3 RESULTS AND DISCUSSION

3.1. Impact assessment of the CSP plant operating in solar-only mode

Table 3 shows the environmental impact associated with the generation of a functional unit of electricity (1 MWh) in the CSP plant operating in solar-only mode. Eight midpoint categories have been included in these analyses, which represent the most relevant in terms of environmental significance. In this scenario it has been assumed that the $6.28 \cdot 10^6$ MJ/yr of auxiliary energy consumed by the plant are met by the combustion of either NG or biogas obtained from biowaste (Bw) or mixed manure (Mx).

Table 3: Characterized impacts in different life cycle phases of the CSP plant operating in solar-only mode with NG and biogas from mixed manure biogas (Mx BG) and biowaste biogas (Bw BG).

Impact category	Units	E&M	C	O&M			D&D	Total		
				NG	Mx BG	Bw BG		NG	Mx BG	Bw BG
Climate change	kg CO_2 eq/MWh	21.1	0.03	4.63	2.19	3.04	0.90	26.6	24.2	25.1
Human toxicity	kg 1.4-DB eq/MWh	12.9	4.70E-03	0.35	0.37	0.38	-0.18	13.1	13.1	13.1
Terrestrial acidification	g SO_2 eq/MWh	150	0.21	8.96	19.0	12.2	7.21	166	176	170
Freshwater eutrophication	kg P eq/MWh	10.1	4.05E-03	0,30	0.32	0.31	-0.36	10.1	10.6	10.6
Marine ecotoxicity	g 1.4-DB eq/MWh	271	0.11	6.94	7.08	7.71	-1.93	276	276	277
Natural land transformation	m^2/MWh	3.42E-03	3.72E-05	8.30E-04	3.55E-04	4.01E-04	5.27E-04	0.005	0.004	0.004
Water depletion	m^3/MWh	0.21	4.34E-03	6.06	6.07	6.07	-1.70 E-03	6.27	6.28	6.28
Fossil depletion	kg oil eq/MWh	7.15	0.01	1.76	0.55	0.58	0.37	9.29	8.08	8.11

*E&M: Extraction and Manufacturing, C: Construction, O&M: Operation and Maintenance, D&D: Dismantling and Disposal.

The results show that when using NG as auxiliary fuel, most (78 %) of the impact associated with climate change derives from the extraction of raw materials and the manufacturing of components employed in the CSP plant (E&M phase), while only 19 % is attributable to operation and maintenance (O&M). A similar profile is observed in all other impact categories with the exception of water depletion, where O&M activities are responsible for most (97 %) of water consumed (6.27 m^3/MWh) by the CSP. Most of this water is used in the condenser of the power block. The intensive consumption of fresh water in wet-cooled CSP plants poses a problem to the widespread deployment of this technology in desert areas. This problem may be overcome using dry-cooled condensers, although these devices incur comparatively higher capital and operating costs and achieve reduced energy efficiencies in thermodynamic cycle.

Substitution of NG with biogas only affected the environmental performance of the system in its O&M phase while all other phases remained unchanged. The potential benefits/detriments of this substitution were limited in all impact categories, due to the low influence of the O&M phase in the overall performance of the plant. The use of biogas (instead of NG) had a small positive influence in some environmental categories like climate change and fossil depletion. For instance, overall greenhouse gas emissions were reduced from 26.6 kg CO2 eq/MWh (NG) to 25.1 (biowaste biogas) and 24.2 kg CO2 eq/MWh (mixed manure biogas). However, despite the renewable nature of the fuel, there was an increase in the environmental impact associated with other environmental categories like terrestrial acidification and freshwater eutrophication.

Figure 2 shows the normalized impacts associated with the CSP plant operating in solar-only mode with NG. The results show that the E&M phase was responsible for most of the environmental impact as a result of damage to the following categories: marine ecotoxicity, fresh water eutrophication, human toxicity and natural land transformation. The second most impacted life cycle phase is O&M, due primarily to damage in the following categories: marine ecotoxicity, human toxicity, freshwater eutrophication and natural land transformation. The results also evidence that other LC phases like construction (C) or dismantling and disposal (D&D) had a very limited contribution to the environmental performance of the CSP plant. Positive impacts derived from the recycling of elements at the end of their useful lives were also limited.

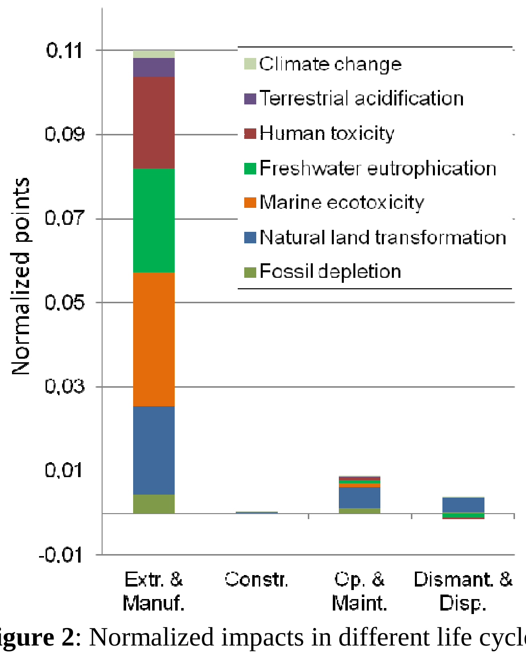

Figure 2: Normalized impacts in different life cycle phases associated with the generation of electricity in the CSP plant in solar-only operation with NG.

Figure 3 shows a comparative analysis of the normalized impacts in different categories associated with the operation of the plant in solar-only mode using NG and biogas as auxiliary fuels. The results evidence that marine ecotoxicity is the most impacted category in all cases, followed by natural land transformation, fresh water eutrophication and human toxicity. Impacts on the marine ecotoxicity category originate primarily from the extraction of raw materials in the E&M phase of the life cycle of the plant, being largely independent from the type of auxiliary fuel used during operation. In particular, contribution to this category is mainly attributable to the use of reinforcing (37%) and chromium steel (12%) in the solar field, the use of copper both in the TES and the power block (18%), and also the HTF (9%). The normalized impact in the climate change and fossil depletion categories are low, due to the limited use of auxiliary fuels during O&M. The substitution of NG with biogas has a limited positive effect on these categories.

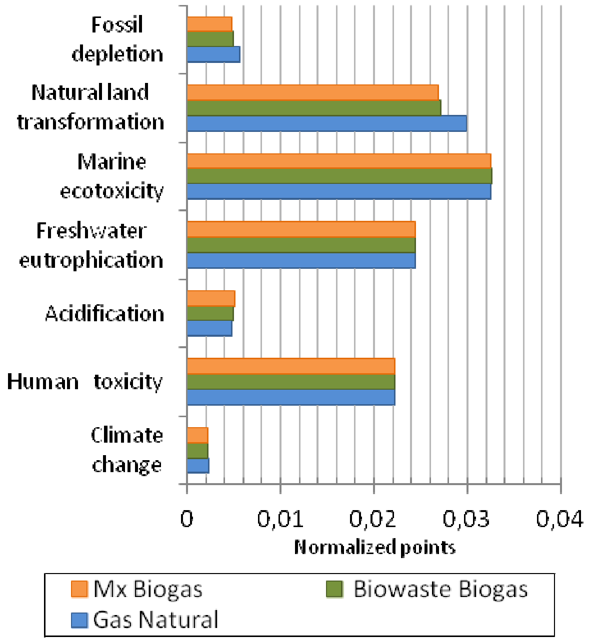

Figure 3: Normalized impacts in different environmental categories determined for the production of electricity in the CSP plant operating in solar-only mode using NG or biogas from different substrates.

Figure 4 shows the aggregated weighted impact (Single Score indicator from ReCiPe Endpoint Europe H/H methodology) associated with the operation of the CSP plant in solar-only mode with NG or biogas as auxiliary fuels. The results evidence a slight improvement in the overall performance of the installation primarily due to reduced impact in the *Resources* endpoint category. This category is highly affected by the consumption of fossil fuels like NG. The type of substrate employed in the production of the biogas has virtually no effect on the environmental performance of the plant.

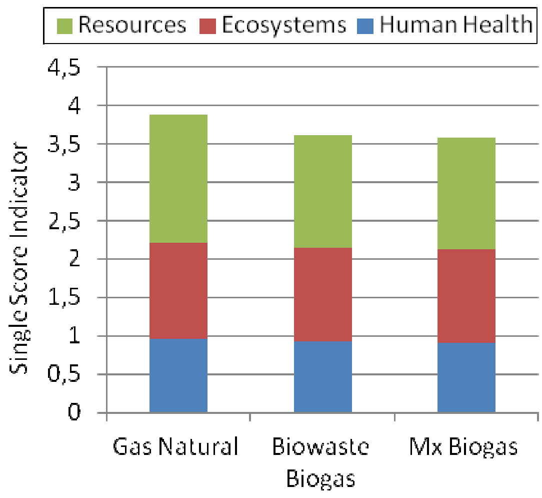

Figure 4: Single Score profile comparing the use of different auxiliary fuels (NG and biogas) in the CSP plant operating in solar-only mode.

3.2. Impact assessment of the CSP plant operating in hybrid mode

Table 4 shows the environmental performance associated with the generation of 1 MWh of electricity in the

CSP plant operating in hybrid mode (12 % of the electricity from auxiliary fuels). The scenarios analyzed include providing this additional energy in the form of NG and also as BM produced from four different substrates: mixed manure; biowaste; grass; and sewage sludge.

Table 4: Characterized impacts of the CSP plant operating in hybrid mode with different auxiliary fuels.

Impact category	Units	Life Cycle of the CSP Plant				
		NG	Mixed manure BM	Biowaste BM	Sewage BM	Grass BM
Climate change	kg CO_2 eq/MWh	124	68.3	96.0	72.9	97.4
Human toxicity	kg 1.4-DB eq/MWh	12.4	20.4	20.8	22.2	22.6
Terrestrial acidification	g SO_2 eq/MWh	215	587	366	259	1,398
Freshwater eutrophication	kg P eq/MWh	9.46	15.8	15.5	17.7	21.8
Marine ecotoxicity	g 1.4-DB eq/MWh	266	401	422	433	463
Natural land transformation	m^2/MWh	0.020	0.008	0.010	0.012	0.011
Water depletion	m^3/MWh	6.26	6.41	6.40	6.48	6.62
Fossil depletion	kg oil eq/MWh	48.4	9.34	10.2	16.8	12.4

The results evidence a notable deterioration in the environmental performance of the CSP plant (per functional unit of electricity) when operating in hybrid mode, as compared with solar only. When NG was used as auxiliary fuel, the characterized impacts for solar-only and hybrid operation in selected categories changed as follows: climate change, from 26.7 to 124 kg CO2 eq/MWh; terrestrial acidification, from 166 to 215 g SO2; natural land transformation, from 0.005 to 0.020 m2/MWh; fossil depletion, from 9.29 to 48.4 kg oil eq/MWh. Variations in other impact categories were less notable. The environmental impact associated with the construction of the two additional boilers (20 MWth) required to operate in hybrid mode is negligible. Hence, nearly all the transformations described are attributable to consumption of auxiliary fuel in the O&M phase.

Of the four BM analyzed in this paper, the one produced from grass (energy crop) generated a significantly higher impact in the climate change category (96.0 kg CO_2 eq/MWh) than the ones produced from the other three substrates (between 68.3-90.9 kg CO_2 eq/MWh), which has been attributed to the residual nature of the latter. The results show significant savings in greenhouse gas emissions (between 23 and 45 %, depending on substrate) as a result of replacing NG with BM. Notable environmental benefits were also observed in other impact categories like fossil depletion and natural land transformation.

However, despite the renewable nature of the BM, the environmental analysis shows detrimental effects in other impact categories, primarily terrestrial acidification but also fresh water eutrophication, water depletion and human and marine toxicity. The high impact in terrestrial acidification has been associated with ammonia emissions during biogas substrate production (in the case of grass biogas), and application of manure digestate (for mix biogas). In the case of marine ecotoxicity and water eutrophication, higher impacts in biomethane scenarios are due to the consumption of electricity during upgrading and biogas generation, but also to emissions during substrate production (emissions of phosphates to water when grass cultivation). Human toxicity impacts in biomethane scenarios are due mainly to the higher electricity consumption, since the disposal of mining spoils and uranium tailings (from fossil fuels contributing to the electricity mix) have emissions with high toxicity to humans. Sewage and grass biogas have higher impacts in these three categories due to their higher electricity use.

Figure 5 illustrates the normalized profile of the CSP plant operating in hybrid mode with NG as auxiliary fuel. In this scenario, most of the environmental damage is attributable to the O&M phase due to the consumption of NG. The consumption of this auxiliary fuel is responsible for 85% and 78% of the impacts in the climate change and the natural land transformation categories, respectively. Due to the higher generation capacity achieved in hybrid mode operation, the normalized impact associated with the Extraction and Manufacturing (E&M) and with the Construction (C) of the CSP plant phases are reduced compared to solar only operation.

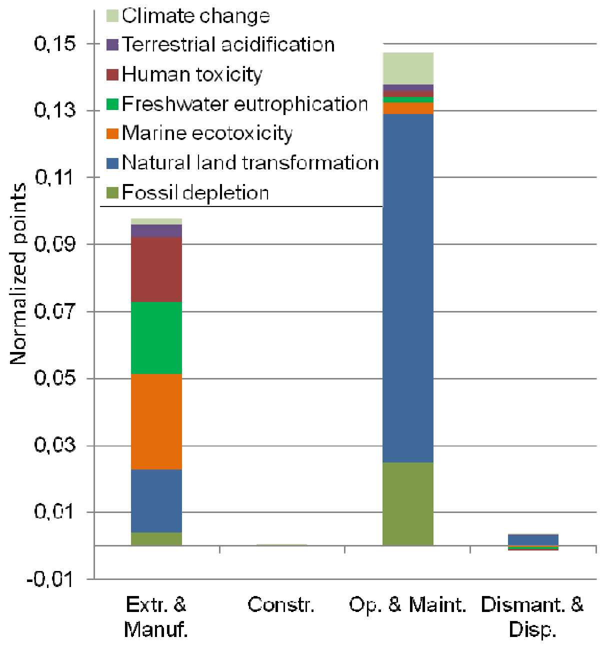

Figure 5: Normalized impacts in different life cycle phases associated with the generation of electricity in the CSP plant in hybrid mode operation with NG.

Figure 6 shows the normalized profiles of the CSP plant operating in hybrid mode with NG or BM from different substrates. As shown in the characterized profiles of Table 4, the substitution of NG with BM improved the environmental performance of the plant in three categories (climate change, fossil depletion and natural land transformation) but had a detrimental effect on some others (mainly terrestrial acidification). According to the methodology employed in this analysis (ReCiPe Europe H perspective), the extent and the environmental significance of the improvements observed in certain categories largely outweighed the detrimental effects observed in some others.

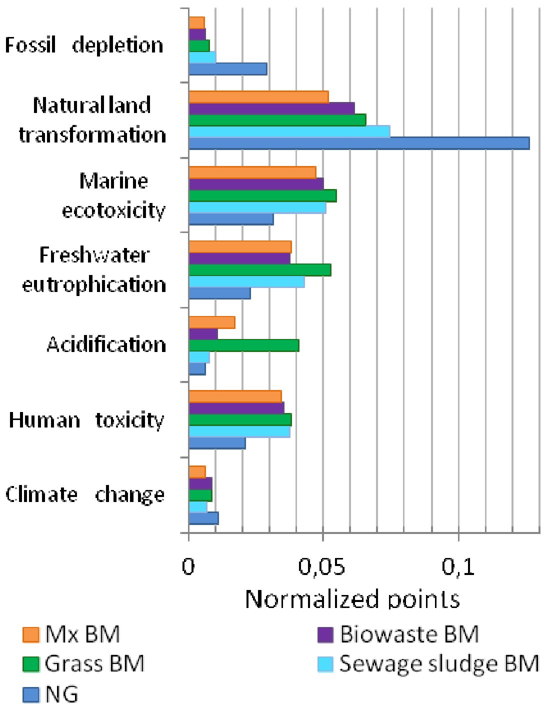

Figure 6: Normalized impacts in different environmental categories determined for the production of electricity in the CSP plant operating in hybrid mode using NG or BM from different substrates.

This is confirmed in Figure 7, which shows the Single Score profile of the CSP plant operating in hybrid mode using NG and BM as auxiliary fuels. The results evidence a significant improvement in the environmental performance of the plant when using the renewable fuels, as compared with NG. Single Score values were reduced from 14.8 Pt in the case of NG to between 6.0 Pt and 7.5 Pt when using BM from different substrates. This evolution is due primarily to lower impact in the Resources category due to reduced consumption of fossil fuels. NG consumption in hybrid mode operation contributes to 83% of the Single Score indicator while BM consumption constributes to between 45-60%, depending on substrate. Upgrading of raw biogas to BM contributes to between 20-24% of the Single Score indicator, while transportation only represents between 0.9-1.0 %.

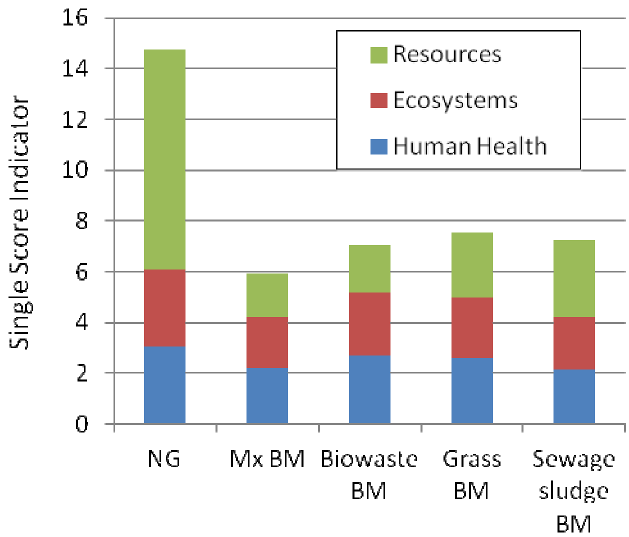

Figure 7: Single Score profile comparing the use of different auxiliary fuels (NG and BM) in the CSP plant operating in hybrid mode.

Of the four BM substrates investigated, the results show that the utilization of cultivated grass produced the highest impact due primarily to the consumption of fuels, fertilizers and other agricultural inputs. Higher environmental savings were achieved using BM and biogas from residual substrates.

4 CONCLUSIONS

The environmental performance of a 50 MWe water cooled CSP plant with 7.5 hour TES operating in solar-only mode and using NG as auxiliary fuel is as follows: climate change 26.6 kg CO2 eq/MWh; human toxicity 13.1 1,4-DB eq/MWh; terrestrial acidification 166 g SO2; freshwater eutrophication 10.1 g P eq/Mwh; marine ecotoxicity 276 g 1,4-DB eq/Mwh; natural land transformation, 4.81 E-03 m^2/MWh; water depletion 6.82 m^3/MWh; fossil depletion 9.29 kg oil eq/MWh. The impact associated with the consumption of NG in solar-only operation is low and most of the environmental damage is associated with the extraction of materials and manufacturing of elements employed in the construction of the CCP plant.

Due to the low contribution of auxiliary fuels to the environmental performance of the CSP plant when it operated in solar-only mode, the potential benefits of substituting NG with biogas in this scenario are limited. The potential savings in greenhouse emissions would represent between 6-10 % of the total. The overall impact of the CSP plant, as determined using Single Score Indicator (ReCiPe Endpoint Europe) methodology, was reduced by between 7 - 8 %, depending on the biogas substrate.

This environmental profile of the CSP plant changes significantly when it is operated in hybrid mode (12 %

electricity from NG): climate change 124 kg CO2 eq/MWh; human toxicity 12.4 kg 1,4-DB eq/MWh; terrestrial acidification 215 g SO2; freshwater eutrophication 9.46 g P eq/Mwh; marine ecotoxicity 266 g 1,4-DB eq/Mwh; natural land transformation, 0.02 m^2/MWh; water depletion 6.24 m^3/MWh; fossil depletion 48.4 kg oil eq/MWh. In hybrid mode operation, most of the environmental damage is associated with the consumption of NG. Hence, the most impacting phase is Operation and Management of the CSP plant. The incorporation of the three gas boilers required to operate the installation in hybrid mode has a negligible effect on the environmental performance of the plant.

In hybrid mode operation, the substitution of NG with BM results in a notable reduction of the impact associated with certain environmental categories (climate change, fossil depletion and natural land transformation). However, despite the renewable nature of the BM, the model shows detrimental effects on other impact categories like terrestrial acidification, fresh water eutrophication, water depletion and human and marine toxicity. The method employed (ReCiPe Endpoint Europe H/H) suggests that the extent and significance of the positive impacts largely outweighs the deleterious effects on certain other categories. The carbon footprint of the CSP plant operating in hybrid mode was nearly halved and the overall impact (Single Score indicator) was reduced by up to 60 % when replacing NG with BM. Higher environmental savings were observed when using BM and biogas from residual substrates, rather than energy crops.

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